Too many $X's$, $Y's$ and $Z's$?

T. F. Caramés and A. Valcarce

Departamento de Física Fundamental,
Universidad de Salamanca, 37008 Salamanca, Spain

J. Vijande

Departamento de Física Atómica, Molecular y Nuclear,
Universidad de Valencia (UV) and IFIC (UV-CSIC), Valencia, Spain.
(Dated: *Version of* February 25, 2013)

Abstract

A large number of new states have been reported during the last few years in charmonium spectroscopy above the charmed meson production threshold. They have been called $X's$, $Y's$, and $Z's$. We reflect on the influence of thresholds on heavy meson spectroscopy comparing different flavor sectors and quantum numbers. The validity of a quark-model picture above open-flavor thresholds would severely restrict the number of channels that may lodge meson-meson molecules.

1

There is general agreement among the hadron physics community that the constituent quark model is a good phenomenology for charmonium and bottomonium below their respective flavor thresholds. It is in this context that discoveries during the recent years of new states in the heavy flavor sector provide tantalizing hints of the underlying dynamics elsewhere in spectroscopy. If this was established it could lead to a more unified and mature picture of hadron spectroscopy. A recurring old question arises again: being some of these new states firmly established (as it is the case of the $X(3872)$), could they be fitted into the quark model scheme or are we in front of the breakdown of such a pattern?

The question above has been the flagship of many experimental and theoretical efforts during the last two decades. In spite of the success of the quark-model picture for the description of the heavy meson spectra [1], the limit for its applicability was questioned, trying to learn why the constituent quark model was wrong [2]. The possible impact of thresholds on the hadronic spectrum came up soon as a relevant mechanism in an attempt to go beyond the adiabatic approximation [3]. The scarce experimental data did not allow to arrive to any definitive conclusion. Such scenario was relived with the hectic times of the θ^+. The existence of this state was, for some time, considered a possible hint pointing to the end of the constituent quark model [4]. At the same time, the first warnings about the experimental data were highlighted. It was noticed that listing all of the mesons from the PDG as a function of J^{PC} indicated that the light hadron dynamics was clearly overpopulated, showing that not all data could be correct. The increasing experimental data in the excited heavy-meson spectra came to reinforce the suspect that the successful quark-model picture for charmonium may get significant distortion from the $D\bar{D}$ threshold region. On the experimental side, the need of caution about the proliferation of low-statistics experimental data has been posed. It has been noticed that experimental signals of 3σ will probably disappear 80% of times [5]. Moreover, there is a well-known difficulty for disentangling resonances from cusps due to the opening of thresholds, what may provide an alternative explanation to some of the recently reported new states [6].

Our purpose in this letter is to discuss how the new set of states reported could offer insight to check the validity of the constituent quark model beyond flavor thresholds. It would severely restrict the number of channels that may lodge meson-meson molecules. Out of the many states recently reported in charmonium and bottomonium spectroscopy, we do not really know how many will survive future experimental screenings. We are still shocked by the θ^+ resonance, seen by so many experiments that later on did not find anything. There is only one state that has been firmly established by different collaborations and whose properties seem to be hardly accommodated in the quark-antiquark scheme, this is the $X(3872)$ [7]. Regarding the zoo of other states that have been proposed, we have to stay tuned but also be cautious [4, 5]. Some members of this XYZ jungle are awaiting confirmation, seen only by one collaboration, like the intriguing charged state $Z(4430)$, seen by Belle but not by BaBar [8]. Other members of this jungle cannot be excluded to fit into the simple quark-antiquark scheme, like the $Z(3930)$ recently identified as the $\chi_{c2}(2P)$ charmonium state [9]. Other experimental signals seen only by a particular experiment, in some of the expected decay modes, or with low statistics, could just be the reflection of the opening of thresholds [6].

Let us start by discussing Fig. 1. In this figure we have plotted the experimental thresholds [10] of four-quark systems made of a heavy and a light quark and their corresponding antiquarks for several sets of quantum numbers, J^{PC}, in three different flavor sectors: $Q = s$, hidden strange; $Q = c$, hidden charm; and $Q = b$, hidden bottom. In every flavor sector we
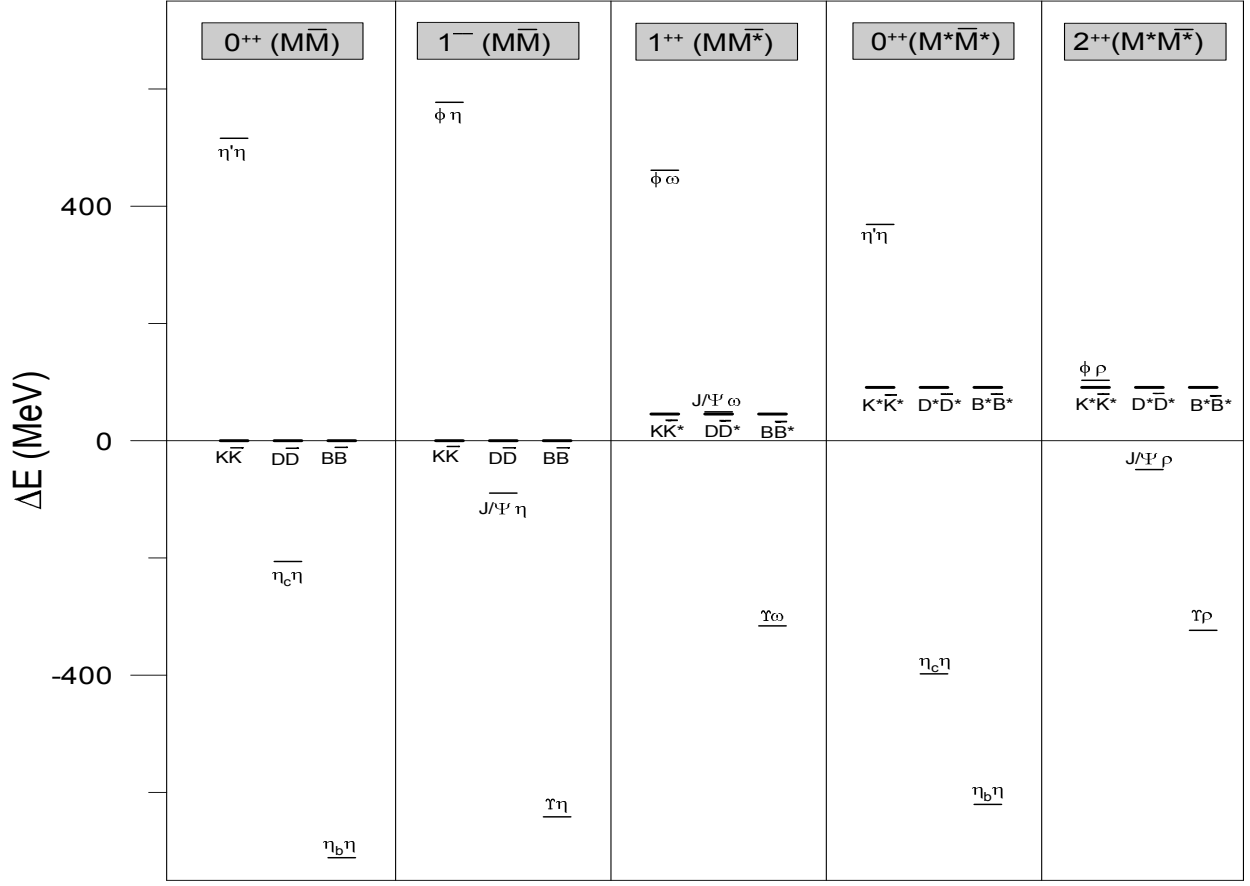
FIG. 1: Experimental thresholds of four-quark systems made of a heavy and a light quark and their corresponding antiquarks, $Qn\bar{Q}\bar{n}$ with $Q = s$, c, or b, for several sets of quantum numbers, J^{PC}. We have set as our origin of energies the $K\bar{K}$, $D\bar{D}$ and $B\bar{B}$ masses for the hidden strange, charm and bottom sectors, respectively.

represent the mass difference with respect to the mass of $K\bar{K}$, $D\bar{D}$ and $B\bar{B}$, respectively. In a constituent quark model picture, the four-quark state $Qn\bar{Q}\bar{n}$ could either split into $(Q\bar{n}) - (n\bar{Q})$ or $(Q\bar{Q}) - (n\bar{n})$. One observes how the general trend for all quantum numbers is that the mass of the $(Q\bar{Q}) - (n\bar{n})$ two-meson system is larger than the mass of the $(Q\bar{n}) - (n\bar{Q})$ two-meson state for $Q = s$, but it is smaller for $Q = c$ or b. It is remarkable the case of $J^{PC} = 1^{++}$ for $Q = c$, where the $(Q\bar{Q}) - (n\bar{n})$ and the $(Q\bar{n}) - (n\bar{Q})$ two-meson states are almost degenerate. The reverse of the ordering of the masses of the $(Q\bar{Q}) - (n\bar{n})$ and $(Q\bar{n}) - (n\bar{Q})$ thresholds when increasing the mass of the heavy quark for all J^{PC} quantum numbers can be simply understood within the constituent quark model with a Cornell-like potential [4]. The binding of a coulombic system is proportional to the reduced mass of the interacting particles. Thus, for a two-meson threshold with a heavy-light light-heavy quark structure, the binding of any of the two mesons does not change much when increasing the mass of the heavy flavor, due to the reduced mass of each meson being close to the mass of the light quark. However, if the two-meson state presents a heavy-heavy light-light quark structure, the binding of the heavy-heavy meson increases with the mass of the heavy particle while that of the light-light meson remains constant, becoming this threshold lighter than the heavy-light light-heavy two-meson structure, as seen in Fig. 1.
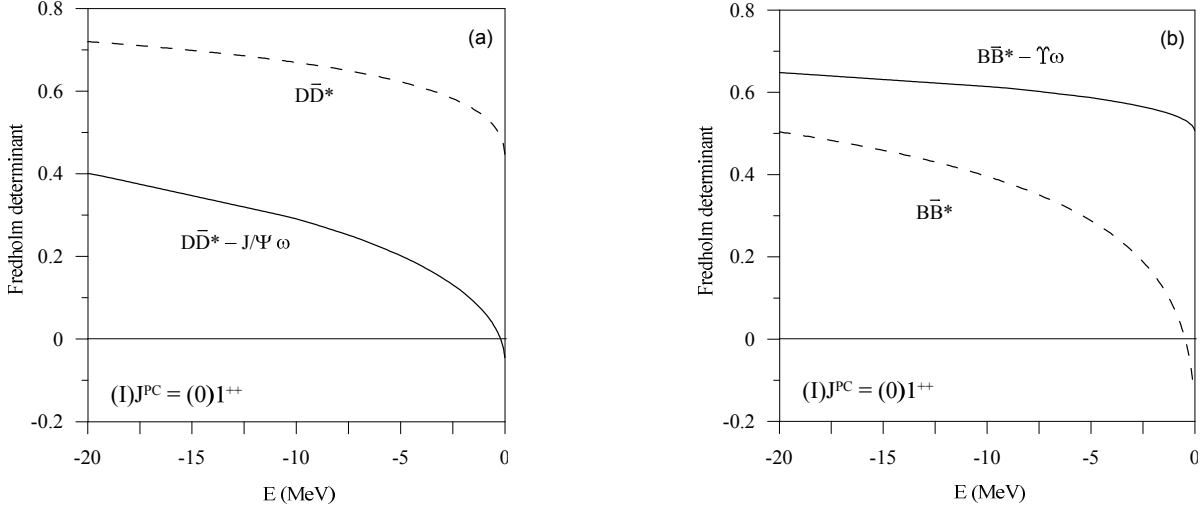
FIG. 2: (a) $(I)J^{PC} = (0)1^{++}$ $cn\bar{c}\bar{n}$ Fredholm determinant [13]. The dashed line stands for a calculation considering only charmed mesons, the solid line includes also the $J/\Psi\omega$ two-meson system. (b) Same as (a) for bottomonium.

Such a picture, together with the absence of long-range forces [11] in a charmonium-light two-meson system, may suggest different consequences for the existence of molecules close to the meson-antimeson threshold. First, the possible existence of such molecules in the hidden-strange sector. If the $K\bar{K}$ interaction is attractive for some particular set of quantum numbers, this two-meson system may be stable because no any other threshold appears below, the dissociation of the molecule being therefore forbidden (see the $Q = s$ states for any J^{PC} quantum numbers in Fig. 1). Such a possibility would become more probable for those quantum numbers where the quark model seems to work worst, those cases where one needs a P-wave in the simplest quark model structure, $q\bar{q}$, but can be obtained in S-wave from a four-quark system. In these cases, the mass of the four-quark system could be even below the predicted lowest quark-antiquark state. This is precisely the idea suggested by Weinstein and Isgur [12] as a plausible explanation of the proliferation of scalar mesons in the light quark sector. They concluded the $J^{PC} = 0^{++}$ and 1^{++} quantum numbers to be the best candidates to lodge a meson-antimeson molecule. These quantum numbers are P-wave in the quark model but S-wave in the four-quark picture and besides they are spin triplet, having therefore an attractive spin-spin interaction [12].

Second, the possibility of finding meson-antimeson molecules contributing to the meson spectrum becomes more and more difficult when increasing the mass of the heavy flavor, due to the lowering of the mass of the $(Q\bar{Q}) - (n\bar{n})$ threshold (see the $Q = c$ or b states for any J^{PC} quantum numbers in Fig. 1). This would make the system dissociate immediately. In such cases, the presence of attractive meson-antimeson thresholds would manifest in the scattering cross section but they will not lodge a physical resonance. These ideas favored the interpretation of several of the experimental signals in charmonium and bottomonium spectroscopy above flavor thresholds as originated from the opening of the threshold and not being resonances [6].

Thus, only a few channels may lodge molecular resonances. As discussed above, there is a remarkable exception to the general rule, the $(I)J^{PC} = (0)1^{++}$ quantum numbers in the charmonium sector. In this case the $(c\bar{n}) - (n\bar{c})$ $(D\bar{D}^*)$ and $(c\bar{c}) - (n\bar{n})$ $(J/\Psi\omega)$ thresholds are almost degenerate, and the attractive $D\bar{D}^*$ interaction together with the cooperative effect of the almost degenerate two-meson thresholds give rise to the widely discussed $X(3872)$ [13].
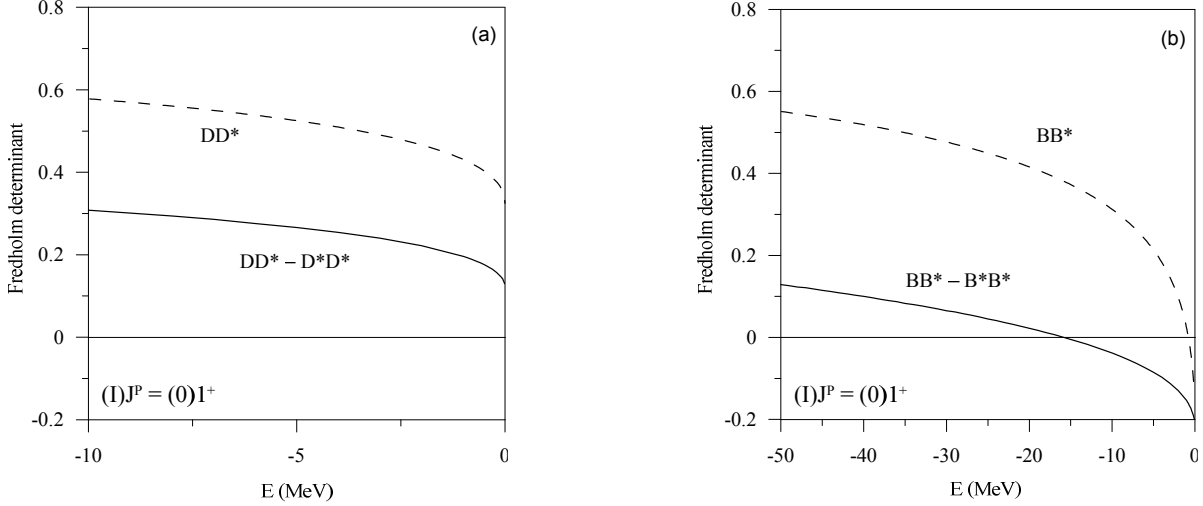
FIG. 3: (a) $(I)J^P = (0)1^+$ $cc\bar{n}\bar{n}$ Fredholm determinant [18]. The dashed line stands for a single channel calculation with the lightest two charmed mesons, the solid line includes the coupling to the relevant excited channels. (b) Same as (a) for bottomonium.

In spite of the general idea that the stability of a system made of quarks comes favored by increasing the mass of the heavy flavor, it becomes more complicated when several vectors in color space contribute to generate a color singlet, as it it the case of four-quark systems [14]. The reason is that, as explained above, the mass of one of the thresholds, $(Q\bar{Q}) - (n\bar{n})$, diminishes rapidly when the heavy quark mass increases (see Fig. 1), making therefore the meson-antimeson system, $(Q\bar{n}) - (n\bar{Q})$, unstable. This simple reasoning of coupled-channel calculations is illustrated in Fig. 2. The calculation is based in an interaction between quarks containing a universal one-gluon exchange, confinement, and a chiral potential between light quarks [15]. As we can see in the left panel, the $D\bar{D}^*$ interaction (dashed line) is attractive, but not attractive enough to generate a resonance (the Fredholm determinant does not go through zero). It is the coupling to the almost degenerate $J/\Psi\omega$ channel (solid line) the responsible for having a bound state just below the $D\bar{D}^*$ threshold. Such an explanation comes reinforced by the recent observation of the decay $X(3872) \to J/\Psi\omega$ [16]. When the mass of the heavy quark is augmented from charm to bottom, the $B\bar{B}^*$ becomes more attractive due to the decreasing of the kinetic energy and having essentially the same interaction. However, the coupling to the lower channel, $\Upsilon\omega$, destroys any possibility of having a bound state (see right panel of Fig. 2). Thus, based on the constituent quark model ideas, one should not expect a twin of the $X(3872)$ in bottomonium spectroscopy like those pointed out in hadronic models based on the traditional meson theory of the nuclear forces or resorting to heavy quark symmetry arguments [11].

One may also think that the proliferation of resonances above flavor thresholds could rely on our poor knowledge of confinement. Confinement is usually described in terms of simple pairwise interactions, but its realization at low energy may be much closer to a many-body force. Refs. [17] have analyzed the stability of $Qn\bar{Q}\bar{n}$ and $QQ\bar{n}\bar{n}$ systems in a simple string model by considering only a multiquark confining interaction in an attempt to discern whether confining interactions not factorizable as two-body potentials would influence the stability of four-quark states. The ground state of systems made of two quarks and two antiquarks of equal masses was found to be below the dissociation threshold. Whereas for the cryptoexotic $Qn\bar{Q}\bar{n}$ the binding decreases with increasing mass ratio m_Q/m_n, for the flavor exotic $QQ\bar{n}\bar{n}$ the effect of mass symmetry breaking is opposite. This effect contrary to bind-

5

ing will be even larger when the mass ratio between the heavy and the light quark becomes larger, as it would be the case of molecular structures in the charmonium or bottomonium spectra.

The discussion on the last paragraph drives us to a brief comment on exotic states $QQ\bar{n}\bar{n}$. In this case the situation is rather different to the nonexotic $Qn\bar{Q}\bar{n}$ system, because the possible dissociation thresholds do not contain states made of a heavy quark and a heavy antiquark, whose binding would increase linearly with the mass of the heavy flavor. Thus, stability will be favored by increasing the mass of the heavy flavor, being much more probable in the bottom sector than in the strange one. This simple coupled-channel effect, that has been discussed in detail in Ref. [18], is illustrated in Fig. 3. As we can see, the coupling to the heavier vector-vector two-meson state makes the system more attractive, the effect being much more important for the system containing two bottom quarks, generating thus larger binding energies. The search of such exotic states is a hot experimental subject for the incoming years in different experimental facilities [19].

Our discussion above may be easily generalized to the possible existence of charged resonances contributing to charmonium or bottomonium spectroscopy. In this case, the coupling to channels containing the light pion destroys the degeneracy between meson-antimeson and charmonium-light two-meson thresholds, an important mechanism for binding four-quark states in the $I = 0$ sector. This excludes, for example, the existence of charged partners of the $X(3872)$, as explained in Ref. [13]. Only one S-wave channel, the $J^{PC} = 2^{++}$, where the coupling to the charmonium-pion two-meson system is prohibited, may be candidate for lodging a resonance close above the $D^*\bar{D}^*$ threshold, as has been already discussed both from the experimental and theoretical points of view [20].

Summarizing, recent experimental data on charmonium spectroscopy have suggested the existence of a large number of states above charmed meson thresholds. They have been baptized as $X's$, $Y's$, and $Z's$, due to their unusual properties not easily explained in terms of simple quark-antiquark pairs. Such proliferation of states has pointed out to the existence of meson-antimeson molecules. In a quark-model picture we have justified how such molecules may contribute to the light meson spectroscopy. In particular, they could explain the existence of non quark-antiquark states for quantum numbers that can be obtained from four-quarks in an S-wave but need orbital angular momentum from a quark-antiquark pair. When increasing the mass of the heavy flavor, the possibility of having meson-antimeson resonances decreases with the mass of the heavy quark. Only in some particular cases the cooperative effect of nearby two-meson channels with an attractive meson-antimeson interaction may produce resonances in the charmonium sector, the $X(3872)$ being the example par excellence. Increasing the mass of the heavy quark destroys the possibility of a twin state in the bottom sector, against the predictions of hadronic models based on the traditional meson theory of the nuclear forces or heavy quark symmetry. Improved confinement interactions considering many-body forces do not enhance the probability of having stable four-quark states in the energy region close to the flavor thresholds. In fact, confining many-body forces would go against the stability of non-exotic four-quark states. Finally, in the exotic sector, due to the nonexistence of thresholds made of two heavy quarks, the stability of two-meson states would increase with the mass of the heavy quark.

The scenario that has been discussed in the present letter is far from taking your favorite random model, finding the J^{PC} states that agree with it and then ignoring, excusing or tweaking the model to apologize for those that do not. It is important to keep the big picture in mind if we are to progress. Focus on the wood, not the trees. Only better

experimental data will give the definite answer to the correctness of the ideas drawn in this letter. The scenario proposed would fit the current experimental data through the simple extension of the constituent quark model we have presented and provides a smooth transition from quark to hadronic degrees of freedom. We hope that our contribution will stimulate a critical analysis of the recent experimental data and theoretical investigations to disentangle resonances from thresholds.

Acknowledgments

[1] N. Isgur and G. Karl, Phys. Today **36** No. 11, 36 (1983).

[2] N. Isgur, Lectures at the Hugs@Cebaf 1993 summer school; Cs. Balázs, M. G. Khayat, and A. Valcarce, Hugs@Cebaf proceedings (1993).

[3] N. Isgur, Phys. Rev. D **60**, 054013 (1999).

[4] F. Close, AIP Conf. Proc. **717**, 919 (2004).

[5] C. Quigg, in *Proceedings of the XIV International Conference on Hadron Spectroscopy*, eConf C110613, Munich, 2011; edited by B. Grube, S. Paul, and N. Brambilla; pg. 217 (2011).

[6] D.V. Bugg, AIP Conf. Proc. **1257**, 303 (2010); Eur. Phys. Lett. **96**, 11002 (2011).

[7] S. K. Choi *et al.* (Belle Collaboration), Phys. Rev. Lett. **91**, 262001 (2003); D. Acosta *et al.* (CDF Collaboration), Phys. Rev. Lett. **93**, 072001 (2004); V. M. Abazov *et al.* (D0 Collaboration), Phys. Rev. Lett. **93**, 162002 (2004); B. Aubert, *et al.* (BaBar Collaboration), Phys. Rev. D **71**, 071103 (2005).

[8] S. K. Choi *et al.* (Belle Collaboration), Phys. Rev. Lett. **100**, 142001 (2008); B. Aubert *et al.* (BaBar Collaboration), Phys. Rev. D **79**, 112001 (2009).

[9] B. Aubert *et al.* (BaBar Collaboration), Phys. Rev. D **81**, 092003 (2010).

[10] K. Nakamura *et al.* (Particle Data Group), J. Phys. G **37**, 075021 (2010).

[11] N. A. Törnqvist, Phys. Rev. Lett. **67**, 556 (1991); Z. -F. Sun, J. He, X. Liu, Z. -G. Luo, and S. -L. Zhu, Phys. Rev. D **84**, 054002 (2011).

[12] J. D. Weinstein and N. Isgur, Phys. Rev. D **41**, 2236 (1990).

[13] T. Fernández-Caramés, A. Valcarce, and J. Vijande, Phys. Rev. Lett. **103**, 222001 (2009).

[14] J. Vijande and A. Valcarce, Phys. Rev. C **80**, 035204 (2009).

[15] J. Vijande, F. Fernández, and A. Valcarce, J. Phys. G **31**, 481 (2005).

[16] P. del Amo Sánchez *et al.* (BaBar Collaboration), Phys. Rev. D **82**, 011101(R) (2010).

[17] J. Carlson and V. R. Pandharipande, Phys. Rev. D **43**,1652 (1991); J. Vijande, A. Valcarce, and J. M. Richard Phys. Rev. D **76**, 114013 (2007).

[18] T. F. Caramés, A. Valcarce, and J. Vijande, Phys. Lett. B **699**, 291 (2011).

[19] S. Cho *et al.* (ExHIC Collaboration), Phys. Rev. Lett. **106**, 212001 (2011); Y. -Q. Chen and S. -Z. Wu, Phys. Lett. B **705**, 93 (2011).

[20] R. Mizuk *et al.* (Belle Collaboration), Phys. Rev. D **78**, 072004 (2008); J. M. Dias, S. Narison, F. S. Navarra, M. Nielsen, and J. -M. Richard, Phys. Lett. B **703**, 274 (2011); T. F. Caramés,

A. Valcarce, and J. Vijande, Phys. Rev. D **82**, 054032 (2010).